The FCC's "White Spaces" decision and its implications for iSchools

Martin Weiss
School of Information Sciences
University of Pittsburgh
Pittsburgh PA 15260
+1 412 624 9430
mbw@pitt.edu

ABSTRACT
New technologies can have a significant impact on what we teach and what we do in an iSchool. In this paper, I describe how a new infrastructure option has emerged for information systems and services. The FCC's "White Spaces" decision involved a large segment of what used to be the NII (National Information Infrastructure) community, a community of considerable affinity to iSchools. In this paper, I argue that this decision is of broad interest to iSchools because: (1) it is a case study that highlights how policy decisions and technology developments interact with each other and (2) many aspects of the follow-up to this decision fall squarely in the domain of iSchools, from the development of white space devices, to building systems to utilize these devices, to building information services to communities that are currently underserved.

Categories and Subject Descriptors
A.m

General Terms
Management, Economics, Legal Aspects.

Keywords
FCC, Telecommunications, Cognitive Radio, Spectrum, Policy

1. INTRODUCTION
While most of the country was busy casting ballots on November 4, 2008, the US Federal Communications Commission ruled that "white spaces" in the television band were available for unlicensed use on a non-interfering basis. While not without controversy, the White Spaces Decision has a significant potential to transform the communications industry and is thus relevant to iSchools.

The white spaces decision has its origins in the wireless revolution, which caused industry participants to explore new approaches to gaining access to radio spectrum that had become more costly and/or congested. Measurements showed that much of the spectrum that had been assigned was underutilized, leading to proposals on how this spectrum might be used more efficiently. Concurrently, advances in microelectronics, software systems, and communications technology led to the emergence of new types of communications systems, such as ultra-wideband (UWB), software-defined radios (SDRs) and cognitive radios. Without delving into the details of these technologies, these systems largely shared the characteristic that advances in and deployment of these systems required actions on the part of the civil sector spectrum administration agency, the Federal Communications Commission (FCC). The "White Spaces" decision is the outcome of one of those explorations – the use of cognitive radio technology to improve electromagnetic spectrum utilization through opportunistic use.

It is often the case that innovation in information system design and implementation requires one or more specific policy actions to enable further development. The white spaces decision discussed in this paper is an excellent example of such a situation – serious commercial development and deployment of devices would not proceed without an enabling policy action. Because of the competing interests, policy action is often difficult because entrenched interest (or incumbents) have a concern about the deleterious effects of this decision. Thus, agencies must often gather data to assuage these concerns, which can require testing prototype systems, which requires significant investments on the part of the proponents. Thus, we have a cycle of incremental commitment on the part of stakeholders. The white spaces decision is an excellent example of innovation that requires government engagement, and could be a good teaching case to illustrate how and why information system innovation may require engagement in the policymaking process.

But the relevance of this decision extends beyond its use as a classroom case to research opportunities for iSchools. There are many opportunities for applying this emergent technology to information systems, especially since, as I argue below, the best application may be in (underserved) rural areas. Cognitive radio technology is still new, so there are still considerable technical research opportunities, as well as systems research opportunities, since cognitive radios have the capability to act in response to environmental changes.

Finally, there are many new research areas that are created in the general domain of interest of iSchools when we consider these kinds of devices. An example of this kind of research is presented to stimulate our thinking and conversation.

2. BACKGROUND
Early in this decade, the US Federal Communications Commission (FCC) began exploring ways in which electromagnetic spectrum might be used more effectively. There were several products of that effort, the earliest being the Spectrum Policy Task Force (SPTF) report [1]. In this report, all under- or un-utilized spectrum were referred to as "white spaces". The SPTF provides a fairly comprehensive discussion of alternatives that might be used individually or in concert to improve spectrum utilization, such as secondary use, opportunistic use, underlay rights, spectrum markets, etc. to utilize these white spaces.

The FCC followed up this report with several dockets exploring some of the more promising approaches identified by the SPTF. In 2002, the FCC released a Notice of Inquiry (NOI) in which comment was sought on using a particular group of these white spaces, those in the broadcast television band [2]. In this NOI, the FCC was "seeking comment on the possibility of allowing unlicensed devices to operate in the TV broadcast bands at locations and times when the spectrum is not being used by authorized services." The rationale for this inquiry was:

> "The Commission noted that unused portions of the TV spectrum appear to be a suitable choice for expanded unlicensed operations. In this regard, the Commission observed that there is significant bandwidth available because each TV channel occupies six megahertz and multiple channels are generally vacant or unused in a particular area. The Commission stated that allowing unlicensed devices to operate on unused TV channels would lead to more efficient use of the spectrum."

This was followed up with a Notice of Proposed Rulemaking (NPRM) [3], based on the feedback received from the NOI in which the FCC detailed a specific approach to using these TV white spaces. Finally, on November 4, 2008, the FCC issued an Order that paved the way for the unlicensed use of the "TV White Spaces" spectrum [4].

As might be expected, the NOI and the NPRM were embraced by some parties, but not others. While it is beyond the scope of this paper to provide a detailed and nuanced analysis of the Comments and Reply Comments, it soon became clear that several key stakeholder groups emerged:

- The broadcast industry, which generally opposed this approach, fearing interference by these "opportunistic" devices, especially at the margins of their viewing areas.
- The Internet-based service providers generally favored this approach, as it provided opportunities for innovation and for bypassing the broadband access market, which is costly to enter.
- The entertainment industry and providers of equipment for that industry, which generally opposed this approach because the wireless microphones that many stage entertainers use also operate in these frequencies.
- Rural wireless ISPs, which favored this approach because the electromagnetic spectrum in the television band was favorable for their application and less congested than the existing unlicensed spectrum.
- Equipment manufacturers and software developers, who were generally in favor of this approach, as it provided new potential markets.

There was also a debate about whether this spectrum should be auctioned or treated as unlicensed spectrum. Many technology industry participants were in favor of using these as unlicensed (see, generally, the Wireless Innovation Alliance), and some prominent telecommunications economists advocated auctioning this spectrum [5]. Hazlett urged abandoning broadcast television entirely and auctioning the spectrum, avoiding the discussion of television white spaces altogether [6].

In order to alleviate the concerns of some of the stakeholders, the FCC required that they use "smart" radio technology that is capable of identifying "the unused TV channels in the area they are located". These radios, also called *cognitive radios*, are leading edge devices that, for the most part, exist as prototypes in research laboratories. To evaluate whether these radios would be capable of performing as needed, the FCC's Office of Engineering and Technology conducted extensive tests of manufacturer's prototypes [7]. Five prototype radios were provided for these tests, which were conducted at nine locations outside of the laboratory. These tests showed that the devices were usually able to detect the presence of both Digital Television (DTV) signals and wireless microphones to very low levels.

2.1 Cognitive radios

The idea of cognitive radios was first proposed by Mitola [8], and subsequent research was summarized in [9]. In a nutshell, cognitive radios are designed to sense their environment, determine whether (or how) the environment matches the application requirement, and, if possible, configure the radio to utilize the environment as long as it is available. If the environment changes, the cognitive radio would respond by reconfiguring themselves to adapt to the new environment. Since these new radios have to work with incumbent devices, the use of signaling between the (incumbent) license holder and the opportunistic user cannot be assumed. Signaling of this kind greatly simplifies interference avoidance.

It turns out that spectrum sensing, especially when the signals are weak and unknown, is a difficult technical problem. Limiting the devices to the television band simplifies this problem somewhat, in that the signal characteristics of television are known and the sensing bandwidth is limited to the TV band. Sensing in the TV band is also simplified because we know where the (licensed) transmitters are and what their signal power is. Thus, we know where to look and what signal level that we might expect.

Spectrum sensing is made more difficult because a radio may be located in place that is in the "shadow" of an obstacle (like a building)[1]. This is a problem because some stations that the radio is communicating with may not be in the shadow and would thus be subject to unwanted interference. Dealing with hidden nodes like this may require the cooperation of radios in the region. This *cooperative sensing* generally improves the sensing of cognitive radios, and requires a communication protocol to enable the radios to share information. One of the interesting research directions is to discover the bounds of (truthful) information sharing when the radios are selfish.

2.2 Characteristics of spectrum use

Radio spectrum and its use have some unique characteristics that deserve mention when considering white spaces. Chief among them are propagation and practical aspects of receivers.

Radio waves propagate mostly as a ground wave[2]. At lower frequencies, radio waves can refract around buildings, can travel over the horizon, and propagate well through the walls of buildings. As the frequencies become higher, refraction becomes more limited, as does the radio wave's ability to propagate over the horizon and through building walls. It turns out that signal attenuation also increases with frequency, so that higher

[1] Such a radio is known as a "hidden node".

[2] At some frequencies, radio waves also propagate as a sky wave, in which the signal is "bounced" off of the upper atmospheric layers, resulting in extraordinarily long propagation.

frequency signals have more limited range than lower frequency ones. To overcome this increasing attenuation, the signal power is often concentrated into a narrower beam using a directional antenna so that reasonable distances can still be achieved.

The propagation characteristics of signals from 700MHz to about 3GHz are generally considered near optimal from a propagation perspective. Thus, they are highly sought after and are used for applications that include television and mobile telephones. If the television band had been located in a less desirable band, it is likely that we would not have seen such a concerted push for the right to use this spectrum opportunistically.

It is also useful to keep in mind some practical aspects of radio system design because it has a significant impact on the way in which spectrum is used. Most radio systems of the kind that we envision for white spaces devices are duplex (two-way). Thus, they usually have a separate radio channel for communication in each direction (uplink and downlink). To minimize interference between these two channels, it is normally desirable to locate them at significantly different frequencies to avoid interference between these channels without the use of costly filters. As a result, most communications systems prefer a "band plan" that consists of two "paired" channels, each being sufficiently large to support the application's requirements.

3. ALTERNATIVES TO WHITE SPACE DEVICES

Cognitive radios, also called *White Space Devices* (WSDs), exist in a continuum of spectrum access options, as described by Buddhikot [10]. On one extreme, we find unlicensed devices that share spectrum, such as WiFi. On the other extreme, we find licensed devices that use exclusive spectrum. Basically, users are faced with a choice of making a tradeoff between price and quality; with shared spectrum unlicensed devices, users obtain uncertain quality at zero price while with licensed devices, users obtain certain quality at a price greater than zero.

WSDs in the television spectrum are unlicensed, so they are close to the WiFi end of the continuum. But because

- WSDs have better sensors (to mitigate interference with license holders),
- WSDs may communicate with each other to coordinate spectrum usage,
- there is (potentially) so much more spectrum available,

we may anticipate higher quality than might be expected of WiFi devices.

Another alternative technology is WiMAX, which boasts higher speeds and longer transmission distances than WiFi. The WiMAX services that are emerging in the US are from the Sprint/Clearwire partnership. These do not have zero price, and since spectrum is shared, the quality is also not certain, though quality can be managed by the service provider.

4. WHAT IS THE EXPECTED IMPACT OF THIS DECISION?

Since devices that might use these white spaces are still in the prototype stage, the immediate impact will be minimal. As these devices become available, we will gradually see service providers building systems on these technologies. For reference purposes, the FCC distinguishes mobile devices from fixed services. Mobile services have lower power thresholds (and hence shorter transmission distances) than fixed services because the chance of interference from mobile devices is higher.

I believe that the initial applications will be for fixed radio systems. There are three major reasons for this. First, since the power required by cognitive radios is still significant, access to the electric grid will be important in the near term. Second, the spectrum sensing/detection time varies from less than a second to two minutes in the FCC test devices [7]. Long spectrum acquisition times are inconsistent with the mobile environment. Finally, fixed devices can transmit at a higher power level.

Studies indicate that the amount of spectrum in the white spaces varies considerably [11]. In general, it is fair to say that the availability of white spaces is much more limited in urban areas than in rural areas. A careful analysis of this question has been done by Brown and Sicker [12]. They conclude that the biggest likely beneficiaries of these systems would be rural communities, where the general availability of white spaces is high and the relatively long propagation characteristics in the UHF band are well suited to the low population densities in these areas. Furthermore, they point out that fewer broadband access options exist, which also serves to make WSD-based access more attractive. To the extent that white spaces are available in urban areas, available spectrum is far more fragmented than in rural areas and may not cover an entire metro area.

But even in urban areas where white space spectrum is available, the emergence of devices that can take advantage of this spectrum means that users of unlicensed wireless systems, like those based on Wi-Fi, can expect better performance. Some industry observers expect a wave of innovation in broadband access (see, for example, [13]), even though the economic models for deploying these new access networks remains unclear (we present some research results below that begin to address this question).

The application of "smart antenna" technology can do much to enhance the feasibility of white space devices. This technology allows for rich spatial diversity. Thus, many devices in the same geographic area will be able to use the same frequency resource without interference.

5. WHAT, IF ANYTHING, DOES THIS MEAN FOR iSCHOOLS?

Broadband access has been an area of interest in many iSchools for some time, though often for different reasons. More technologically oriented iSchools would have an interest in exploring the technical aspects of building white spaces devices; more systems oriented iSchools would have an interest in considering the new options offered by these devices; and more service oriented iSchools would have an interest in considering and evaluating the extent to which these systems could provide new opportunities to meet the community's information needs.

5.1 Illustrating information systems innovation

It is incumbent on us, as teaching faculty, to give our students a deeper appreciation of the policy context of information systems. Policy matters because it can drive the requirements of information systems, drive the behavior of these systems, and, guide innovations in this domain. In the introduction, I showed how the white spaces decision was an exemplar of the latter – to enable further development of this technology, changes in government policy were necessary.

5.2 Technology research

There are many opportunities for technology research in white spaces. This is particularly true since there are no commercial devices yet. While some of the basic technologies that are required for implementation and product launch will (and should) be accomplished by equipment manufacturers, there are still many research opportunities for universities that have iSchools. These include:

- Innovation in cognitive radio design for white spaces
- Innovation in spectrum assignment, including secondary use markets, spectrum trading markets, and markets in interference rights
- Improving the energy efficiency of cognitive radios for mobile devices
- Reducing the chance of interference by improvements in detection, including:
    - Using exogenous information to improve detector performance
    - Optimal cooperation among cognitive radios (even those that might be competing for the same white space spectrum)
- Economics of cognitive radios and intelligent radio systems
- Behaviour of systems of WSDs, i.e., cooperation, collusion, and competition of potentially selfish devices
- Using white spaces effectively in urban environments, which may constitute new approaches in power control and/or intelligent antenna systems (such as MIMO).

5.3 Applications and systems

When new technologies enter the marketplace, the opportunities to apply the new technology multiply. While there is nothing new about broadband access, there is something new about broadband that has the characteristics of white space devices. Because of the uncertain nature of the available spectrum, the system could be subject to significant variations in available bandwidth, depending on the system's location. Because the radios themselves have significant processing capabilities and are able to respond to their environment, it becomes important to understand the behavior of systems of intelligent radios.

5.4 Services

The proponents of unlicensed use of white space devices have high hopes for providing services to communities of that are currently either underserved or unserved. The greatest promise for white space based systems is in rural areas, as I remarked above. Thus, it is conceivable that a new broadband capability could be deployed in these areas. In most cases, rural communities have less access to libraries, information services and medical systems. Because of the availability of broadband systems capable of propagating long distances, it may be feasible to deploy a new generation of public safety communication system that can provide not just dispatch-oriented voice communication, but a system capable of data, image and video communication that can help reduce the response time of first responders.

6. SOME RELATED RESEARCH RESULTS

The iSchool at Pitt has research capabillities that are service, technology and application oriented. Research in alternatives to spectrum access has been going on at Pitt for most of this decade, though it has not been in unlicensed WSDs like those that were approved by the FCC in the November decision. Nonetheless, some of the research results that have been obtained can inform about some of the possible impacts of WSDs and can serve as an example to illustrate what is possible at an iSchool.

In [14], we report on the results of a project that studied secondary spectrum use. Unlike unlicensed WSDs, this paper was studying a system in which secondary users would purchase temporary usage rights from license holders on a market. So, while the details of the study are different in significant ways from unlicensed WSDs, the overall context was similar.

To aid in understanding the results, it is necessary to say a bit more about the details of the model. First of all, Agent-based Computational Economics (ACE) is a "bottom up" tool that is being used by some economists to observe market outcomes without some of the sometimes restrictive assumptions that have to be made in analytical economics. When using ACE, researchers create software agents that are capable of interacting with each other. These interactions include buying and selling goods, bidding in auctions, etc. Researchers can control the rules that govern the interactions (market rules) and the behavior of agents. ACE researchers can collect a variety of data about the interactions (such as prices paid, choices made), which can then be used to gain insight into the effects of certain behavioral and market rules.

In our analysis, we were interested in incorporating technological parameters (such as propagation and quality of service) as well as some behavior ones (such as bounded rationality and opportunism). The latter set were included because we wanted to be able to study the bounds within which such a market would be feasible; given the realities of today's wireless marketplace, the ability to model the consequences of a small number of license holders was important.

While it is relatively easy to see how license holders could benefit from monetizing unused spectrum through secondary use, understanding the behavior of secondary users is a bit more challenging. In our model, we allow secondary users to choose between unlicensed use, secondary use, and license acquisition. Secondary use rights are purchased at an auction, where multiple primary and secondary users might be competing. In the results being reported here, we examine how these choices were made under different circumstances. These included the number of consumers, the size of the area being covered, and the sensitivity to quality (represented by differing values of α). Figure 1 illustrates what users choose when secondary use is added as an access option.

This figure, which models 13 simulated consumers and 19 license holders – a medium-sized scenario – presents several different results:

- Each group of six bars represents a coverage area of different size, from 250 to 1000 meters.
- Each column within a coverage area shows the outcomes with different degrees of sensitivity to quality, from less to more as you move from left to right.

- The cross-hatched bars represent results when secondary use is permitted and the clear bars show the results that obtain without secondary use.
- Color represents the choices made by secondary users, where
    - red represents users that chose to acquire licenses,
    - blue represents users that chose unlicensed use, and
    - green represents users that chose secondary use.

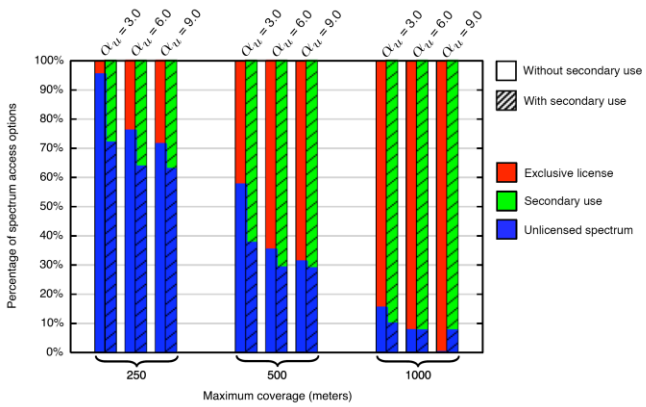

Figure 1 - Impact of secondary use on user behavior

Clearly, without secondary use, users were divided into either unlicensed or licensed use. When secondary use was permitted, our results show that adding secondary use completely eliminates the demand for licenses, as users have cheaper access options with equivalent quality. This could result in lower prices at auction for spectrum licenses.

The choice that users make also depends on their sensitivity to quality and the coverage area. Not surprisingly, as the user's sensitivity to quality increases, their willingness to choose unlicensed decreases, even when secondary use is added. Similarly, we see that larger coverage areas result in fewer users choosing unlicensed spectrum. This is because the chance of interference increases with the service area, so the quality decreases as the service area increases.

Although the model did not explicitly consider unlicensed WSDs, this result has has relevance. While the price for spectrum is zero for both WiFi unlicensed service and WSDs, it is reasonable to assume that WSDs will be more costly than WiFi devices, so they represent the same kind of cost/quality tradeoff faced by the users in our modelled scenario. Thus, the introduction of unlicensed WSDs will provide more options for users and simultaneously should reduce the demand for licensed spectrum.

While we did not model rural use explicitly, we can get a sense of this scenario by examining user behavior at lower user densities. Figure 2 is like Figure 1 with only five secondary users and 19 license holders. We can see that relatively more users choose unlicensed service for all coverage areas. This is expected, given that the interference would be lower for smaller numbers of users.

If we allow the number of license holders and secondary users to vary, we obtain the result that is shown in Figure 3. When the numbers of either are small, secondary use is not chosen. When the number of providers (license holders) is small, opportunism prevails and users make other choices. When the number of consumers (secondary users) is small, then unlicensed is an attractive option.

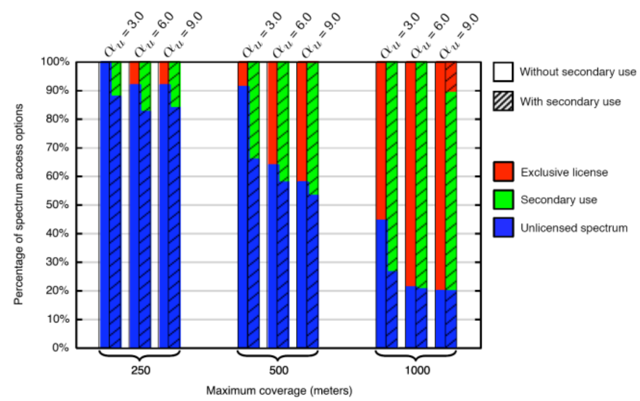

Figure 2 - User behavior at lower user densities

This figure suggests that we might expect secondary use to be evolutionary. That is, as more users enter the market, we might expect an increasing number to choose secondary use. Furthermore, a move away from unlicensed WSDs to a market-based approach would require the active participation of sufficient license holders to be successful.

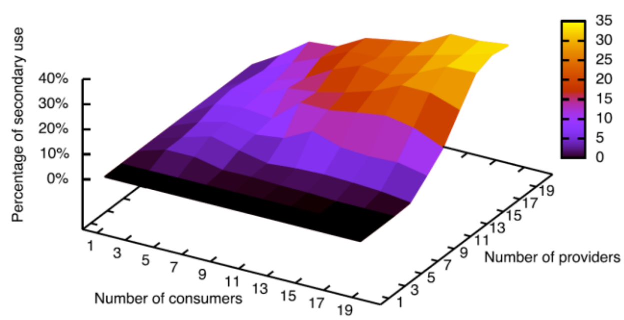

Figure 3 - Secondary use as a function of the number of primary and secondary users

In the TV bands affected by the White Spaces order, the market-based secondary use and the unlicensed use of white spaces are largely disjoint phenomena. The unlicensed WSDs covered in the FCC's Order would exist in geographic, temporal and spectral regions outside of the television broadcaster's license, so the broadcaster would not have license rights in these regions anyway. Thus, the market-based secondary use that was examined in this research could emerge in conjunction with unlicensed WSDs if broadcasters found it more valuable to lease spectrum to secondary users at certain times of day than to use it for television broadcasts.

While this scenario seems unlikely if one considers a broadcaster's entire viewing area, it could be much more likely if we imagine an area within the broadcaster's license domain where cable television subscriptions are very high. Since the broadcaster would not lose market share by sub-leasing spectrum in this area to secondary use, they may find a secondary use transaction financially superior. This would require changes in public policy, however, since broadcasters have limited ability to use this spectrum for purposes beyond its allocation.

7. CONCLUSIONS

One of the distinguishing features of many iSchools is a systems-oriented approach. A key variable of this view is the context of a system – government policy is often a key contextual element. But government policy can go beyond this to *shaping* what is possible. Helping our students achieve a richer understanding of the role of policy in information systems is often best achieved by constructing teaching cases (or, at least, developed examples).

The FCC "White Spaces" decision is an excellent exemplar of this kind of teaching case. Without explicit public action, it would have been a poor investment on the part of researchers in academe and industry to focus on cognitive radio, as it would have remained at the idea stage. Thus, it would have been moot to consider the cost/performance combination that these systems may offer in the future. Because of the FCC's interest in this (culminating in their Nov. 4 Order), numerous corporations have invested in building prototype WSDs, some of which have been demonstrated at the Dynamic Spectrum Access Networks (DySPAN) conferences. While they are still in the early development stage, it is not too early to re-imagine the information systems and services that might use them.

From a research perspective, WSDs and the associated technologies offer a rich set of opportunities in the domain of iSchools. The technologies themselves and their implementation details (eg. markets) require more study. Also, since these devices offer new tradeoffs in cost, quality and coverage, these WSDs may offer new opportunities for service delivery at prices and performance levels that were impossible before. For iSchool researchers, this means that capabilities such as telemedicine in rural areas may now be feasible and cost effective where it once was not.

Beyond that, iSchools can, and should, be leaders in implementing and making use of this new, emergent technology. There are many opportunities across the traditional domains of iSchools that may benefit from considering this new class of devices. I invite you to join me in thinking through and acting on these emerging research opportunities.

8. REFERENCES

[1] Spectrum Policy Task Force Report. Federal Communications Commission ET Docket No. 02-135. November 2002. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf .

[2] Federal Communications Commission. In the Matter of Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band. ET Docket 02-380. December 11, 2002. http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-328A1.pdf.

[3] Federal Communications Commission. In the Matter of Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz band. Notice of Proposed Rulemaking. FCC 04-113. May 13, 2004. http://fjallfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf.

[4] Federal Communications Commission. In the Matter of Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz band. Second Report and Order and Memorandum Opinion and Order. FCC 08-260. November 4, 2008. http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf .

[5] Comments of Charles L. Jackson, Dorothy Robyn and Coleman Bazelton in WT Docket 06-150 and PS Docket 06-229, June 20, 2008.

[6] Hazlett, T. Don't Let Google Freeze the Airwaves. Wall Street Journal. October 3, 2008. See also http://arstechnica.com/articles/culture/dtv-transition-to-yesterday.ars.

[7] Jones, S.K., Phillips, T.W., Van Tuyl, H.L., and Weller, R.D. Evaluation of the Performance of Prototype TV-Band White Space Devices, Phase II. FCC OET Report 08-TR-1005. October 15, 2008. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-2243A3.pdf

[8] Mitola, J. Cognitive radio – model-based competence for software radios. Licentiate Thesis. KTH. Stockholm. September 1999.

[9] Akyildiz, I.F., Lee, W.L., Vuran, M.C., and Mohanty, S. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Computer Networks 50 (2006), 2127-2159.

[10] Buddhikot, M. Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges. 2nd International IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007). April 17-20, 2007. pp. 649-663.

[11] Scott, B. and Calabrese, M. Measuring the TV "White Space" Available for Unlicensed Wireless Broadband. New America Foundation Policy Paper. November 18, 2005. http://www.newamerica.net/files/archive/Doc_File_2713_1.pdf .

[12] Brown, T.X. and Sicker, D.C. Can Cognitive Radio Support Broadband Wireless Access? 2nd International IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007). April 17-20, 2007. pp. 123-132.

[13] Ganapati, P. FCC White Spaces Decision Kicks Off the Next Wireless Revolution. Wired. November 5, 2008. http://blog.wired.com/gadgets/2008/11/fccs-decision-t.html.

[14] Tonmukayakul, A. and Weiss, M. A study of secondary spectrum use using agent-based computational economics. Netnomics 2009 (forthcoming).